# *Towards advancing scientific knowledge of climate change impacts on short-duration rainfall extremes*

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## Towards advancing scientific knowledge of climate change impacts on short-duration rainfall extremes

Hayley J. Fowler[1*], Haider Ali[1], Richard P. Allan[2], Nikolina Ban[3], Renaud Barbero[4], Peter Berg[5], Stephen Blenkinsop[1], Nalan Senol Cabi[6], Steven Chan[1,8], Murray Dale[7], Robert J. H. Dunn[8], Marie Ekström[9], Jason P. Evans[10], Giorgia Fosser[11], Brian Golding[12], Selma B. Guerreiro[1], Gabriele C. Hegerl[13], Abdullah Kahraman[1,8], Elizabeth J. Kendon[8], Geert Lenderink[14], Elizabeth Lewis[1], Xiaofeng Li[1], Paul A. O'Gorman[15], Harriet G. Orr[16], Katy L. Peat[1,16], Andreas F. Prein[17], David Pritchard[1], Christoph Schär[18], Ashish Sharma[19], Peter A. Stott[8,20], Roberto Villalobos-Herrera[1,21], Gabriele Villarini[22], Conrad Wasko[23], Michael F. Wehner[24], Seth Westra[25], Anna Whitford[1]

* corresponding author (h.j.fowler@ncl.ac.uk)

1 School of Engineering, Newcastle University, Newcastle upon Tyne, UK
2 Department of Meteorology and National Centre for Earth Observations, University of Reading, Reading, UK
3 Department of Atmospheric and Cryospheric Sciences, University of Innsbruck, Innsbruck, Austria
4 National Research Institute for Agriculture, Food and Environment, RECOVER, Aix-en-Provence, France
5 Hydrology Research Unit, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
6 Willis Research Network (WRN), Willis Towers Watson (WTW), London, UK
7 JBA Consulting, UK
8 Met Office Hadley Centre, Exeter, UK
9 School of Earth and Ocean Sciences, Cardiff University, UK
10 Climate Change Research Centre and the ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, New South Wales, Australia
11 Scuola Universitaria Superiore IUSS, Pavia, Italy
12 Met Office, Exeter, UK
13 School of Geosciences, the University of Edinburgh, Edinburgh, UK
14 Royal Netherlands Meteorological Institute, De Bilt, the Netherlands
15 Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, USA
16 Environment Agency, Horizon House, Bristol, UK
17 National Center for Atmospheric Research (NCAR), Colorado, USA
18 Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland
19 School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia
20 College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK
21 School of Civil Engineering, Universidad de Costa Rica, Ciudad Universitaria Rodrigo Facio, San José, Costa Rica
22 IIHR-Hydroscience & Engineering, The University of Iowa, Iowa City, Iowa, USA.
23 Department of Infrastructure Engineering, The University of Melbourne, Victoria, Australia
24 Computational Research Division, Lawrence Berkeley National Laboratory, San Francisco, USA
25 School of Civil, Environmental and Mining Engineering, University of Adelaide, South Australia, Australia

### Abstract

A large number of recent studies have aimed at understanding short-duration rainfall extremes, due to their impacts on flash floods, landslides and debris flows and potential for these to worsen with global warming. This has been led in a concerted international effort by the INTENSE Crosscutting Project of the GEWEX (Global Energy and Water Exchanges) Hydroclimatology

Panel. Here, we summarise the main findings so far and suggest future directions for research, including: the benefits of convection-permitting climate modelling; towards understanding mechanisms of change; the usefulness of temperature-scaling relations; towards detecting and attributing extreme rainfall change; the need for international coordination and collaboration. Evidence suggests that the intensity of long-duration (1 day+) heavy precipitation increases with climate warming close to the Clausius-Clapeyron (CC) rate (6-7% $K^{-1}$), although large-scale circulation changes affect this response regionally and rare events can scale at higher rates, while localised heavy short-duration (hourly and sub-hourly) intensities can respond more strongly (e.g., 2xCC instead of CC). Day-to-day scaling of short-duration intensities supports a higher scaling, with mechanisms proposed for this related to local-scale dynamics of convective storms, but its relevance to climate change is not clear. Uncertainty remains in the influence of many factors, such as large-scale circulation, convective storm dynamics, and stratification, on changes to precipitation extremes. Despite this, recent research has increased confidence in both the detectability and understanding of changes in various aspects of intense short-duration rainfall. To make further progress, the international coordination of datasets, model experiments and evaluations will be required, with consistent and standardised comparison methods and metrics, and recommendations are made for these frameworks.

## 1. Introduction

Climate models project a general intensification of extreme rainfall during the 21st century on continental to global scales, consistent with observed trends [1][2]. However, large uncertainties in regional patterns and the rate of change [3][4] hamper the development of efficient adaptation strategies for flooding (IPCC 2013), presenting a formidable challenge to public safety, services, critical infrastructure and the economy. There is a particular lack of understanding around changes to short-duration (sub-daily) rainfall extremes which are especially hazardous and responsible for fatalities [5], as they lead to flash floods, landslides and debris flows that occur with little warning [6]. Short-duration, high intensity rainfall events are also responsible for pollution incidents from combined sewerage networks [7]. Cities are particularly vulnerable to floods generated by heavy short-duration rainfall due to ageing drainage infrastructure systems designed to deal with lower historical rainfall intensities, and an increase in impermeable surfaces. Better understanding of the impacts of global warming on sub-daily (particularly hourly to 3-hourly) extreme precipitation is therefore crucial for societal adaptation [8], through the management of the water environment (see Orr et al. this issue) and application to design of stormwater drainage infrastructure systems (see Dale et al. this issue), among others.

Over the last six years an enormous international effort, led by the INTENSE (INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes) Crosscutting Project on Sub-Daily Extremes [9] of the GEWEX (Global Energy and Water Exchanges) Hydroclimatology Panel, has produced multiple studies which have advanced scientific knowledge of climate change impacts on short-duration rainfall extremes, enabling substantial advances in quantifying historical changes and providing improved physical understanding for regional projections (Figure 1). These range from the development of convection-permitting models (CPMs) and idealized model experiments to the collection and assessment of precipitation observations. Very high-resolution CPM simulations (e.g. [10]) can explicitly simulate km-scale motions in convective storms and how these change with global warming but do not yet resolve turbulent cloud dynamics. CPMs have enabled the simulation of local storm dynamics [11], e.g. the diurnal cycle of convection [12], orographically-enhanced extreme precipitation [13], the spatial structure of rainfall and its duration-intensity characteristics [14][15], and hourly and sub-hourly precipitation intensities [16][17].

INTENSE also led an effort to collate and quality-control a global database of sub-daily precipitation data across multiple continents. The Global Sub-Daily Rainfall (GSDR) dataset [18] comprises observations from >25,000 gauges, quality-controlled using open-source Python codes [19]. This quality-controlled data has been used to develop UK-wide gridded 1km resolution hourly precipitation products [20], blended gauge-radar-satellite datasets [21] and to examine the ability of hourly gauge data to capture hourly rainfall extremes [22]. The GSDR has also been used, together with reanalyses and remotely-sensed products, to produce global 0.1° daily and 3-hourly precipitation probability distribution climatologies for 1979–2018 [23]. These add to existing merged products as a key resource for the community to validate climate model outputs [11] and provide a significant platform for future development.

INTENSE has provided a global assessment of observed extreme rainfall characteristics in the GSDR [24] and, by linking with CPM simulations, used to better understand drivers of change. Trend analyses in the UK [25] and US [26] have shown that trends in winter extremes are emerging first in hourly precipitation for both magnitude and frequency statistics and that these can in part be linked to rising temperatures. Similar work over the Netherlands has shown that most hourly precipitation extremes are part of large-scale circulation systems [27]. Large-scale drivers of hourly precipitation extremes have been explored further, by linking these to atmospheric circulation patterns over Europe [28][29], the US [30], Australia [31], and globally [32]. Analysis of CPMs has established the large-scale precursors of small-scale storms over the UK [33]. This work has enabled access to rainfall extreme metrics for impact researchers, and provided a platform for the exploration of the role of storm dynamics in state-of-the art climate models.

However, whilst progress is evident in model capability, leading to new insights to km-scale atmospheric responses to climate change, the use of CPMs to guide decision-making in a real-world context is still challenging (Orr et al. this issue). This is primarily because of under-sampling of either model uncertainty at these finer scales (e.g. relying on output from a single, or small sample of, model(s)), or wider global climate model (GCM) uncertainty (i.e. the number of CPM-GCM combinations). From an extremes-perspective, the relatively limited length of a CPM simulation can also be a limitation for CPMs to provide guidance on future change. For example, analyses of precipitation 'extremes' are still often focused on relatively frequent events from an impacts perspective (e.g. 99th percentile of hourly rainfall) whereas decision-makers are mostly interested in rare events such as the '1 in 100 year' event.

On a more positive note, the advent of CPMs allow for a more detailed assessment of the applicability of the Clausius-Clapeyron (CC) relation to different environmental conditions and storm intensities and structures. The CC-relation describes the relationship between saturation vapour pressure and temperature or, more simply, the moisture holding capacity of an airmass relative to its temperature. According to this relationship, specific humidity increases at approximately 6-7% per degree warming ($K^{-1}$) near to the Earth's surface [34]: a rate used as a first approximation to indicate how rainfall extremes may change with a warming climate. It is assumed that this relationship can be transferred because rainfall extremes tend to occur when the atmosphere is at, or near, saturation and they are limited by the amount of atmospheric moisture converged into the storm; therefore, changes to rainfall intensities are, to a first approximation, expected to scale with CC [35]. This CC rate of increase has been confirmed for observations and projections of daily extreme rainfall intensities when averaged globally (e.g. [1][2][36]), even if it is modulated by dynamical changes regionally [4]. For shorter durations, however, intensities can scale at higher than CC rates in some cases (e.g. [37]) and evidence suggests this is caused by physical processes related to dynamical feedback mechanisms in clouds (e.g. [38]).

In this paper we present the outcomes of expert discussion around scientific knowledge of climate change impacts on short-duration rainfall extremes held at a Discussion Meeting at the Royal Society in February 2020. The research challenges associated with understanding future impacts on rainfall extremes are extensive and covered in a dedicated review paper (Fowler et al., in press). Here we focus specifically on topics that garnered specific attention by the participants of the Royal Society meeting and seen as interest areas for future work, including *the benefits of convection-permitting climate modelling*, *towards understanding mechanisms of change*, *the usefulness of temperature-scaling relations*, *towards detecting and attributing extreme rainfall change*, and *the need for international coordination and collaboration.* In a concluding section we then consider the gaps that remain and how we might further advance scientific knowledge of climate change impacts on short-duration rainfall extremes and their links to decision-making.

## 2. The Benefits of Convection-Permitting Climate Modelling

Over the past decade, computational advances and improvements in CPMs have enabled a step-change in the capacity of the climate modelling community to simulate short-duration rainfall extremes (see Kendon et al. this issue). CPMs substantially improve the simulation of local storm dynamics and better capture the details of convective organisation but some biases remain, such as an overestimation of heavy rainfall due to under-resolved cloud processes such as entrainment (e.g. [15][39] and Prein et al. this issue). CPMs are not able to capture the small-scale details of storms, with rainfall cells tending to be too large with too much heavy rainfall (Prein et al, this issue, [40]). However, they are able to capture mesoscale organisation and perform well in cases of large convective storms, and overall give a much more realistic representation of hourly precipitation than convection-parameterized models.

CPMs produce quite different projections of change to short-duration rainfall extremes than convection-parameterized models, especially in convection-dominated environments, with studies so far suggesting increases in the future intensities of short-duration extremes at the CC rate or greater [41]. INTENSE CPM results over Northern Europe suggest that storms will become more intense and longer in duration [42] with climate warming, but that storm profile does not significantly change [43]. This is similar to results from radar observations, where storms were found to become more intense and larger in size with warmer temperatures [44]. It also corroborates work with CPMs over the US [45] but is different to storm profile changes identified in observations in Japan [46] and Australia [47][48] which found intensification of the storm core but a smaller storm size with warmer temperatures. The seasonality of intense hourly events was also found to change with global warming, with more events in autumn months in Europe, at the expense of summer [49].

CPMs have been run for multi-year climate simulations over many regional domains, e.g. UK [15][10][50], southwest Germany [39], Sydney, Australia [51], the Colorado headwaters [52], the Alps [12][53][54], Scandinavia [55], and whole continents, e.g. the USA [56], Europe [49][57] and Africa [58]. Coordinated CPM intercomparison projects, such as the CORDEX Flagship Pilot Study (CORDEX-FPS) [59], the European Climate Prediction System (EUCP) [60] and the first ensemble of CPM projections from the UK Climate Projections (UKCP) [61][62] have enabled the first multi-scale assessments of precipitation extremes, from coarser convection-parameterized models down to CPMs, and improved understanding of uncertainties in extreme rainfall projections [63]. Short runs of CPMs have even been run globally [64][65], and it is also possible to close the gap between planetary and convective scales in more idealized simulations (see O'Gorman et al. this issue). However, the growth in data volume from these very high-resolution simulations has given rise to problems in data sharing between scientists working with these models, and standard CMIP/CORDEX approaches for data sharing might be usefully replaced by more efficient approaches [66].

We recommend that the capacity to share and compare model outputs, in combination with the use of high-resolution observational products for model evaluation, could aid climate model development and increase confidence in model performance among practitioners. The comparison of CPMs at different horizontal resolutions and the sharing and benchmarking of events/scenarios is in its infancy but has started under projects like EUCP and community efforts such as CORDEX-FPS. This will help to answer fundamental questions that are robust across different models, such as the benefits and features of using CPM resolution (e.g. [67]). We recommend that further investigation is made of adequate and ideal model setups for CPMs (e.g.[68]) and why this varies according to modelled region, e.g. Europe vs US. We suggest that multi-scale approaches, with downscaling from GCMs and RCMs to CPM scales, may also be enhanced by the use of machine learning approaches to connect models and processes at different scales, and perhaps enable improved representation of structural uncertainties between different climate models or the development of new convective parameterizations [69][70]. We suggest that CPM output could also help guide the development of scale-aware parameterizations [71]. In general, we acknowledge the scope for further analysis of the large number of existing simulations. We recommend that better use is made of these simulations, with the sharing of CPM data among modelling groups. However, we suggest that the development of CPM reanalysis products using numerical weather prediction (NWP) simulations would be a useful addition to current model sets. The ongoing C3S initiative, CERRA, is taking a lead here to produce a 5.5 km dynamically-downscaled ERA5 regional reanalysis: https://climate.copernicus.eu/copernicus-regional-reanalysis-europe-cerra.

Widely used in CPMs are pseudo global warming (PGW) experiments, allowing us to explore the implications of a warming atmosphere on different precipitation regimes [72][73]. Key to this has been the use of PGW simulations to explore in-storm changes due to thermodynamic effects, e.g. [34]. A key challenge to address in PGW experiments is the convergence between model projections and observations regarding the existence of super-CC scaling rates and understanding the mechanisms behind them (see Lenderink et al. this issue). However, in regions where dynamical processes are important, such as changes to large-scale circulation patterns, we recommend that a full downscaling from GCM to CPM scales should be preferred. Although CPM analyses have so far mainly concentrated on 'peak intensity' changes over fixed durations, e.g. daily, multi-day, hourly, etc., likely structural changes to different storm types in the future are important to understand for both impacts and for updating of design guidance (see Sharma et al. this issue).

Many characteristics of larger storm systems (e.g. cyclones, fronts) may be better understood using CPMs, with their better representation of the mesoscale structures associated with slantwise instabilities within fronts. We suggest that the objective identification of different types of storm system and their associated hazards (heavy precipitation, strong winds) in CPMs may help to identify likely spatial and temporal changes to hazards, as well as the likelihood of change in dominant event types, with global warming. One example of this is change to within-storm characteristics, such as the frequency of intense short-duration precipitation bursts within longer duration events, which are better simulated by CPMs. Indeed, the improved representation of advection from sea to land and the triggering of convective showers in CPMs may be crucially important for understanding changes to precipitation type, for example where stratiform changes to convective [61]. We recommend the need for more research on changes to storm type, organization, orientation, and movement [45] using CPMs, which are better at representing storm movement and morphology and potential changes to within-storm characteristics than convection-parameterized simulations (Prein et al. this issue). Additional studies are also necessary to examine whether biases in GCM/RCM storm and convection propagation account for the discrepancies in trends between observations and climate models. We recommend also considering the possibility of unprecedented 'black swan' events or storm types. Together, this work may allow us to establish the effect of changing temporal storm patterns on geophysical/urban responses.

## 3. Towards Understanding Mechanisms of Change

INTENSE and other initiatives have established a firm scientific basis for the relation between temperature and extreme precipitation intensities at daily and hourly durations; an infographic on the acquired knowledge and the missing pieces is shown in Figure 2 and explained in the following. The rate of intensification of rainfall extremes under climate change depends on various processes that range from the microscale to the synoptic scale and planetary scale. Published scientific evidence suggests that daily precipitation extremes for large-scale precipitation increase with temperature at approximately the CC rate (6-7% $K^{-1}$) over large regions [1][2][36], while warm, convective storms can potentially increase at higher rates (~1-2xCC)[37]. Uncertainty remains in the influence that changes to large-scale circulation dynamics, temperature stratification (affecting atmospheric stability), and latent heat release will have on the intensification of extreme rainfall, particularly for short-duration extremes. Studies indicate that local effects are important, but changes in precipitation efficiency, cold pool dynamics, and wind shear effects are still poorly understood. This is partly due to the concentration of studies on 'peak intensity' changes, the more complex analysis methods necessary to investigate change in small-scale cloud processes, a lack of consistent analysis methods and a lack of observational datasets to fully evaluate CPMs. Recent observational and CPM studies have enhanced understanding of how these processes interact and how they might affect future extreme rainfall and a full review of our current understanding is provided in Fowler et al. (in press).

We suggest that theory and idealized modelling experiments of convection in limited-size domains have the potential to provide further guidance as to where and when higher rates of change of precipitation extremes with climate warming (e.g. 2xCC) should be expected. For climate warming experiments in the simplest setting of radiative convective equilibrium (RCE), warming is greater higher in the atmosphere than at lower levels, hence increasing the dry static stability of the atmosphere. In these RCE experiments we see the atmosphere following close to a moist adiabat and the response of short-duration precipitation extremes is close to CC [74][75][76], although changes in precipitation efficiency can cause deviations from CC at lower surface temperatures [77]. When warming is uniform in the vertical, experiments yield higher rates of increase in precipitation extremes [78][79] but since this experimental design imposes an increase in moist instability this is an expected result. Thus, we suggest that to make theoretical progress it would be helpful to develop a simple framework of convection (possibly in a disequilibrium state) in which the vertical profile of warming is not externally imposed and yet super-CC rates of increase of precipitation extremes can in some cases be realized in response to climate warming.

There are some well understood mechanisms. Storms will tend to intensify due to increased latent heat release and updraft velocities and increases in moisture-convergence producing larger storms (Fowler et al. in press). These increases will be dampened by enhanced atmospheric stratification due to a fundamental thermodynamic effect related to changes in the moist-adiabatic lapse rate in a warmer atmosphere which increase static stability both in the tropics where the atmosphere stays close to a moist adiabat [80] and in the extratropics [81]. These competing effects of increased latent heating versus increased static stability are crucial for changes in updrafts speeds and thus precipitation rates [78] (O'Gorman et al this issue)., The changes in stratification also drive large-scale geographical patterns in surface warming and significant changes in precipitation frequency and amount [82]. This effect is particularly important in tropical regions and in extratropical summer conditions, and is a more robust response than large-scale circulation changes that, for e.g., dominate precipitation changes during the European winter [82]. Changes to large-scale atmospheric dynamics are clearly important and not well-researched. We recommend that it is important in future work to establish the relative contributions of atmospheric stratification, dynamics and thermodynamics to changes to extreme precipitation not just for peak intensities but with event-based analysis according to storm/precipitation type (see Moron et al. this issue). We suggest that this will enable the disentangling of processes causing extreme events and move us further towards answering questions like, why is intensification higher for the most extreme events [83][84][85], and is this a simple result of changes in frequency mixing with changes to intensity?

It will also enable us to establish the importance of small-scale dynamics vs. large-scale dynamical changes on storm intensification and frequency. Local dynamical scaling might enhance precipitation within an event but a large-scale shift of circulation patterns might move the moisture sources sufficiently to affect the regional-scale response [86][87]. For example, large-scale circulation effects caused by Arctic amplification may lead to change in jet stream positioning over Europe, but overall there is low understanding due to multiple driving mechanisms [88]. However, an increased gradient in moisture from low to high latitudes determined by the CC relation will lead to more moisture transport into the Arctic which will alter cloud/radiative/precipitation characteristics which, in turn, affect Arctic amplification [89]. Similarly, changes in large-scale dynamics can strongly affect where precipitation extremes occur most frequently in both the subtropics and the tropics. Uncertain dynamical influences must be explored to establish more clearly the likely response of large-scale systems and the role they will play in enhancing/dampening thermodynamically-driven extreme precipitation increases with warming.

Changes to small-scale cloud physics will also be important. In particular, continental convection is generally much less "efficient" than maritime convection but its efficiency can be greatly increased if it organises into a mesoscale convective system. At the moment little is known about differing responses over the ocean and continents. However, if changing temperatures lead to different modes of mesoscale organisation of the convection that could provide a mechanism for a different response. The processes involved in the organization of extreme precipitation events are multi-fold and vary by region. Extremes can self-organize due to feedbacks that are triggered by small-scale processes (e.g., convective self-aggregation) or they can be organized and intensified by larger-scale processes (e.g., fronts, orographic lifting). High-end extreme events are, however, typically related to process interactions that amplify extreme rainfall [90]. In this case, synoptic-scale processes usually trigger, organize, steer, and amplify mesoscale processes [91] [92]. The role of changes in convective organization in the response of extreme precipitation to climate change remains uncertain and is an important avenue for future research [93]. It is possible that there may be a difference, too, arising from the dominance of different microphysical mechanisms: e.g. liquid vs ice dominated clouds and ice multiplication. All of these processes must be further understood to fully understand potential regional changes.

## 4. The Usefulness of Temperature-Scaling Relations

INTENSE evaluated the potential usefulness of temperature-scaling for projections of changes to precipitation extremes. It established that the scaling relation between extreme daily rainfall and day-to-day variability in temperature, the 'apparent' scaling [94], across the globe approximately follows the CC rate or below [95] when using a moisture component in temperature-scaling [96][97]. This is consistent with both observed trends and projected changes to extreme daily rainfall intensities [2]. An INTENSE study also indicated that sub-daily precipitation extremes are in some regions increasing at faster rates, at up to three times, than would be expected from atmospheric moisture increases alone [37]. This is consistent with super-CC apparent scaling (rates larger than 6.5% $K^{-1}$) found for sub-daily rainfall intensities in some locations (e.g. [98][99][100][101]). In CPMs apparent scaling with near-surface temperature is approximately CC during warm days but decreases on the hottest days, as also seen in observations; scaling is consistently CC or above if a moisture-component is included [102]. It is still uncertain what this will mean for future projections of changes to precipitation intensities, due to the unknown effect of large-scale circulation changes [43], but evidence is emerging that sub-daily rainfall intensification is related to an intensification of flash flooding, at least locally [44].

CPMs have been used to establish some of the mechanisms for enhanced rainfall intensities from local in-storm effects [38] and from urbanisation [103]. However, it is uncertain whether these apparent scaling rates are suitable for projecting change to extreme precipitation with future warming. For example, present day scaling may alias changes in meteorological regimes (e.g. stratiform to convective) with temperature that are not relevant for climate change [94]. Temperature scaling could be expected to be the same for day-to-day variability and future warming when considering some factors that affect extreme precipitation, such as moisture, latent heating and hydrometeor type, but there is no a priori physical reason to think it will be the same when considering changes in temperature stratification or mesoscale and synoptic circulations which can also strongly affect extreme precipitation [4][78][104]. Nevertheless, we suggest that evaluation of the scaling relationship in observations compared to climate models can identify model weaknesses and potential under-simulation of change.

One of the main issues in establishing whether scaling is a useful prediction mechanism is the lack of comparability among current studies, which use different metrics of 'extremeness,' different datasets, different scaling methods, and often lack quality control methods. A full comparison of existing methods – a meta-analysis on scaling – would provide information on the consistency of scaling across space and whether this is a likely candidate to explain and predict future changes to extreme precipitation from warming. This should focus on standard metrics and examine the difference in using scaling variables such as surface air temperature, surface dew point temperature or atmospheric observations at higher levels of the atmosphere, using quality-controlled and standardised datasets. Additionally, all studies should include confidence intervals on their scaling curves to allow uncertainties to be better established and should publish their analysis scripts since small details in methodology can have significant impacts on resulting scaling rates [105]. Furthermore, multi-decadal-long large-region or continental studies of intensification and scaling should be executed to distinguish the climate signal of event intensification from local day-to-day noise ([26], also see discussion in Wasko this issue). This would also help to illuminate potentially coherent spatial patterns of change to extreme precipitation frequency and intensity, and the potential effects of regional dynamics and local-scale effects resulting from e.g. urbanisation [103].

It would also help to understand how storm-tracked scaling rates compare to gauge-level rates and whether CC scaling (and perhaps changes with warming) are different within different parts or types of storms (e.g. [47]). In particular, event attribution studies of individual tropical cyclones in the US suggest that precipitation totals averaged over a storm's duration and spatial extent scale close to CC. However, in the heaviest precipitating regions of intense tropical cyclones, precipitation rates scale at 2xCC or higher [106][107]. This is thought to be due to storm structural changes in warmer environments [108] but requires further understanding. Further complicating the issue is how climate change will affect tropical cyclone frequency. While most, but not all, tropical cyclone permitting climate models (horizontal resolutions of 20-50km) project a decrease in the global tropical cyclone count with global warming, there are competing viewpoints of whether this is realistic [109][110][111]. While the community agrees that the fraction of tropical cyclones that become intense will increase, a decrease in intense tropical cyclone frequency is possible if the total storm count decrease is large. To facilitate these analyses, it would be useful to update the definitions of storms that produce heavy rainfall and to produce automated tracking systems: we currently define storm structures based on satellite images but could produce much more detailed classifications based on new radar products (e.g. [44][112]), among others. These could for example include vertical thermodynamic profiles, indispensable for understanding the water and energy cycle [113].

## 5. Towards Detecting and Attributing Extreme Rainfall Change

Given the damages often associated with extreme short-duration rainfall, there is growing importance on the reliable monitoring, attribution and prediction of such events. A key component of this, in recent years, has been increasing interest in the detection and attribution of large-scale changes in extreme precipitation and in the attribution of weather events involving extreme precipitation, which seeks to calculate the extent to which anthropogenic factors have increased the likelihood or intensity of particular types of event (e.g. [114]). There have also been attempts to demonstrate the close link between conventional detection and attribution and event attribution [115].

A subjective expert assessment, by the authors, of our current confidence in both the detectability and understanding of changes in various aspects of extreme short-duration rainfall is provided in Figure 3. Understanding, shown on the vertical axis, is based on both the volume of literature and its consistency while detectability, shown on the horizontal axis, is based primarily on the volume and quality of observations. Aspects on one side or the other of the diagonal line mean that confidence is greater in understanding or attribution respectively. Extreme precipitation metrics are shown in blue, selected severe storm types shown in red, and processes relevant across storm types shown in black. Daily precipitation extremes from station data are well observed over North America, Western Europe and parts of Asia and Australia but are sparse in the developing nations [116]. Attribution to human influences of changes in daily precipitation extremes over land at large-scales is well established [117][118], although uncertainties remain with respect to larger magnitudes of change in observations than GCMs, the representativeness of stations both in spatial distribution and scale, and the level of internal rainfall variability in GCMs. However, observational uncertainties over oceans are large as a result of both retrieval algorithms and temporal sampling. Nevertheless, the widespread increasing trend in observed annual maximum 1-day precipitation increases confidence and follows physical and climate model expectations (Clausius-Clapeyron); with about 18% of moderate daily precipitation extreme events over land now attributable to warming [115].

Sub-daily precipitation extremes are less well observed in general over land [119], hence we have less confidence in our ability to detect changes. There has also been less work on detection studies of 3-hour and 1-hour precipitation, including extremes. However, a growing number of observational analyses indicate increases in the frequency and/or intensity of 1-hour extreme precipitation in, e.g. Australia [120], parts of China [121], SE Asia [122], Europe [123][124] and North America [26]; with [120] detecting large increases outside the range of natural variability (up to 3xCC) for hourly extreme precipitation in Australia. A full review of this topic can be found in Fowler et al. (in press) and suggests that extreme sub-daily precipitation will increase at the Clausius-Clapeyron rate, or higher. This, coupled with the fact that we expect large-scale circulation changes to affect sub-daily precipitation extremes less than thermodynamic drivers and that we have reasonable understanding of the thermodynamic feedbacks, means that the confidence in our understanding of the effect of climate change on extreme sub-daily precipitation is nearly as high as for daily extreme precipitation.

Event attribution studies of extreme rainfall events have used a variety of approaches including the statistical analysis of observational data and the analysis of large ensembles of climate model simulations. There is no *a priori* reason to expect different types of intense storms to respond in the same way to higher temperatures, and studies have so far not separated storm types. In fact, there is substantial evidence that changes to the most intense storms may be quite different than changes to more frequent, less intense storms of the same type [125][111][126]. The literature on the effect of climate change on tropical cyclones is rapidly expanding due to advances in computing and high-resolution climate modelling. Intense tropical cyclones (TC) are readily identifiable in both the real world and in appropriate high-resolution simulations [127], placing them relatively high and to the right in Figure 3, with attributable increases of the risk of extreme rainfall found for Hurricane Harvey [128][107]. Intense extratropical cyclones (ETC) are well-simulated in a wider class of climate models but are not as readily identified in models or reanalyses [129][130] placing them to the left of intense tropical cyclones, although event attribution was performed for the August 2016 flood-inducing event in South Louisiana [131] Atmospheric rivers (AR) and frontal systems pose similar identification problems [132][133] so they are placed at the same position at intense ETC on the detection axis. A sparsity of literature on extreme precipitation changes in these two storm types places them lower on the understanding axis [134]. For robust results from event attribution, observational and modelled datasets of sufficiently high resolution are required, stretching current capabilities for event attribution to the utmost. But with ensembles of CPMs becoming available there is a strong potential for event attribution of localised extreme rainfall to make a big step forward in the next few years.

Changes in specific humidity are well-observed to scale with temperature over oceans according to the CC relationship and have been attributed to human activities [135]. Quality observations and sound theory place it in the upper right corner of Figure 3. Changes in severe convection, on the other hand, are difficult to observe over wide regions of the planet but are well simulated in very-high-resolution models not requiring convective parameterizations [136] [137], placing severe convection far to the left but relatively high in Figure 3. Temperature scaling is not independent of changes in large-scale circulation nor changes in modes of large-scale variability. Changes in large-scale circulation such as the Walker and Hadley cells can affect the locations of storm tracks of all types [88]. These changes are generally well understood and observed [138]. Changes in modes of inter-annual/decadal variability, such as the El Niño Southern Oscillation or the Pacific Decadal Oscillation, are more difficult to detect due to a relatively short observational record. Literature on this subject is extensive but not conclusive [138]. Temperature scaling of short-term precipitation extremes, as discussed in this paper, involves these changes in circulation and humidity but also potential changes in storm structural dynamics. These effects could include changes in vertical uplifting, changes in convection, changes in translational speeds and other structural changes, as previously discussed.

## 6. The Need for International Coordination and Collaboration

To further advance knowledge there is a clear need to foster international coordination and collaboration around the identified scientific gaps in understanding. We suggest that a variety of frameworks could be used to facilitate this, such as collaborative meetings, enabled by programmes such as the European COST Actions or the US National Science Foundation's AccelNet programme. Follow-up meetings could also be arranged as satellite meetings, or specialised meetings, e.g. American Geophysical Union Chapman conference, or BIRS Banff workshop. In addition, funding or networking opportunities with intergovernmental organizations (e.g. International Monetary Fund, World Bank, World Health Organisation) or re-insurance firms should be explored. We recognise a need to improve connections between the climate research community and related disciplines such as statisticians, weather forecasters, and the climate impacts community, as well as policymakers and practitioners (see Figure 4 for a schematic illustrating the benefits of the crossover between disciplines). This may also help communities focussing on sustainable development to be made aware of developments in climate science, and to allow them to be part of shaping funding streams and research directions useful for decision-making processes. We suggest that is particularly important to include connections to scientists in developing countries to build data availability in data-poor regions of the tropics, and for capacity-building, as infrastructure may be more vulnerable in the low latitudes.

INTENSE, and the development of the GSDR dataset in particular, has been an exemplar of international coordination and collaboration, but issues still hinder progress. These include data availability, quality issues and biases in datasets; for example much of the GSDR dataset is not shareable to the international community although efforts are underway to identify mechanisms for dataset maintenance and updating to ensure the GSDR's long-term legacy. While progress has been made in this respect through initiatives such as Copernicus [139], an improved international capacity to both monitor change and share data remains a significant challenge [140]. In the meantime, the development of derived products, such as the Expert Team on Climate Change Detection and Indices (ETCCDI [141]), provide the scientific community with information on these restricted datasets. Since results can change significantly with quality control, we recommend good quality-control of datasets in all scientific studies (e.g. [19][20]). We also recommend taking account of biases in different data products and identify potential shortcomings in short and sparse gauge data records. We recommend the increased use of different data types, such as remotely sensed (i.e. satellite and radar) datasets, reanalyses and blended products, each with their own strengths and weaknesses; together these can further enable understanding of how extreme precipitation is changing and help to elucidate key mechanisms.

We encourage more internationally coordinated intercomparison studies of CPMs. Such efforts have started with CORDEX-FPS, EUCP and efforts focusing on organized convection in Argentina and over the Tibetan Plateau (http://rcg.gvc.gu.se/cordex_fps_cptp/). We suggest that comparison studies with standard metrics and coordinated model design criteria will further the understanding of model biases and shortcomings. This should lead to model improvements, greater understanding of mechanisms causing increases in extreme precipitation and allow the evaluation of uncertainties. One key deficiency of existing models is land-surface feedbacks; we recommend a priority should be improving the representation of the soil/water table which was not designed for CPMs and seems to have a strong impact, especially on dry bias. Incorporating physically-based hydrologic models within climate model land surface components could also help to improve the simulation of local feedbacks in CPMs that partly drive convective processes in continental regions. Similarly, improvements in the representation of urban landscapes would improve related atmospheric feedbacks, such as rainfall intensification from urban heat island effects [103], and CPMs could be really useful for examining the effects of planned urban/peri-urban expansion on micro-climates, guiding local adaptation measures, such as implementation of city wide green infrastructure. Alongside this, we suggest that comparison of CPM vs gauge observations will be useful in understanding network density effects, which have also been observed from radar vs gauge comparisons [22][142], and may severely affect our estimates of regional return levels, crucially needed for design decisions.

## 7. Conclusions and Future Directions

Over the last six years the INTENSE Crosscutting project of the GEWEX (Global Energy and Water Exchanges) Hydroclimatology Panel has led a concerted international effort to advance scientific knowledge of climate change impacts on short-duration rainfall extremes. This culminated in a Discussion Meeting at the Royal Society, London, UK where a number of experts discussed the state-of-the-art in this research field and how to address remaining gaps. Improvements in observations and the advent of CPMs has led to considerable advances in the understanding of thermodynamic drivers of changes and their impacts on peak intensities, with much clearer understanding of the potential role of relationships between day-to-day temperature variabilities and precipitation (scaling) in projecting changes to rainfall extremes. Progress has also been made on the understanding of changes to storm spatial structures and profiles with warming with considerable evidence of changes with climate change. Considerable progress has also been made on the understanding of local dynamical enhancements causing super-CC scaling, such as latent heat release, enhanced vertical uplift and moisture convergence. Less well understood is the moderating role of large-scale circulation on thermodynamic changes and the climate change impacts on small-scale cloud dynamics (i.e., turbulence) and cloud microphysics and their effects on changing extreme precipitation.

To further advance this research field, we recommend that an event-based conceptual framework would be a useful approach to help clarify differences among various rainfall mechanisms and scaling rates. This focus on local event properties is however balanced by a need to gain a better understanding of the impact that potential changes to large-scale circulation patterns could have on intense rainfall extremes. These questions are complementary, and of particular interest was the possibility of circulation-driven changes to the dominant event type across regions. Despite high variability, observed changes can be vital to evaluate and challenge climate model simulations. This can be done either by comparing attributed changes to model simulated changes, or through emergent constraints where observations narrow uncertain climate model projections.

Finally, to make this ever-increasing understanding useful to decision-makers, we recommend that the international community must consider language, headline messages and communication mechanisms as well as experimental design [143]. We suggest that there is also a need to connect the atmospheric science community (e.g., climate modellers) with the hydrologic, and climate impacts, community. Our current understanding is limited to changes in extreme precipitation (this article is a good example of this), which is only part of the equation when we are interested in future flooding. With the recent advances in atmospheric modelling, we recommend now is the time to take the next step and tackle the question of how this relates to changes in flooding. Although some instances exist of translation of current state-of-the-art model results into flood design guidance, e.g. [144], this is still in its infancy (see Wasko et al. this issue for an extensive review). To increase uptake from decision-makers we may need to change our current approach to adopt alternative modelling strategies such as storylines [145]. As well as producing a 'likely' range of change we need to consider the 'plausible worst case' scenario as the most important risks rarely lie within the 'likely' range, e.g. [146]. This includes dealing with the modelling of unprecedented yet physically plausible extremes and rare events such as the '1 in 100 year' event or 'Probable Maximum Precipitation' which are often missed in current analyses. We suggest that understanding the extent to which the results are consistent across the frequency distribution is also an important research priority.

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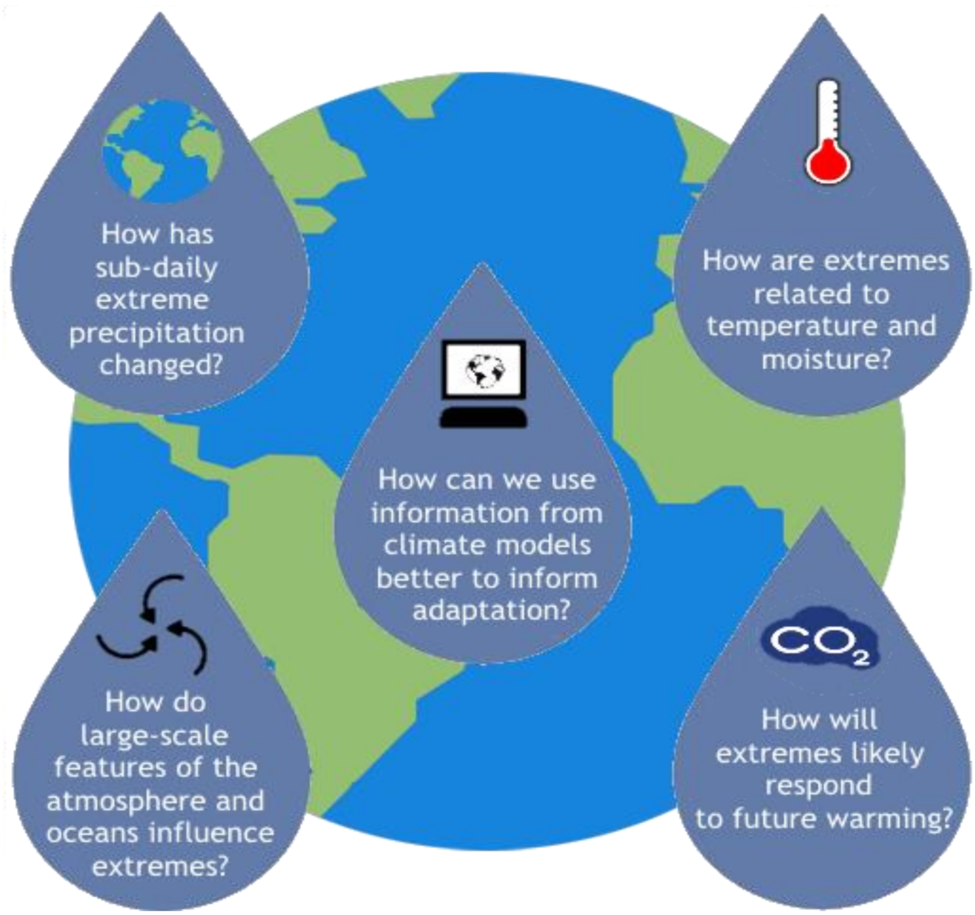


**Figure 1:** The INTENSE project's key questions.

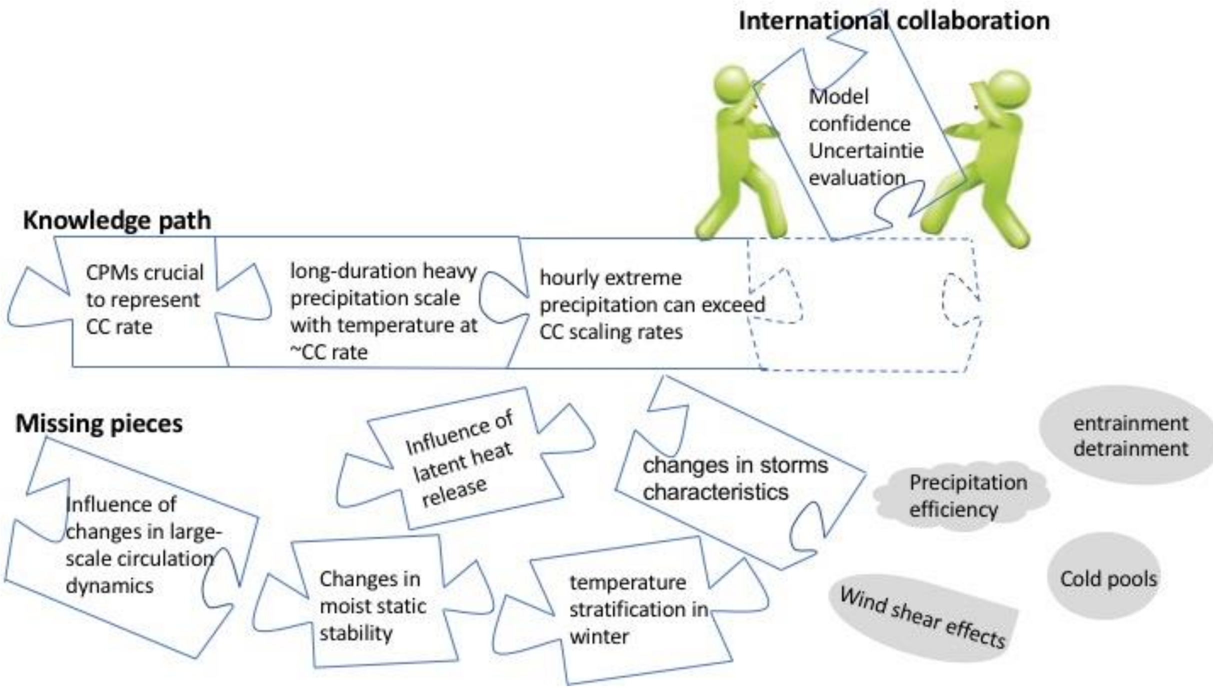


**Figure 2:** Knowledge path on relationship between precipitation extremes and global warming: consensus and missing pieces. Additional studies are required to dissipate uncertainties linked to the influence of large-scale circulation dynamics, latent heat release and moist static stability, changes in storms characteristics and temperature stratification. International collaboration is needed to increase model confidence, to evaluate uncertainties, and to advance scientific knowledge on poorly understood phenomena like cold pools, wind shear and precipitation efficiency.

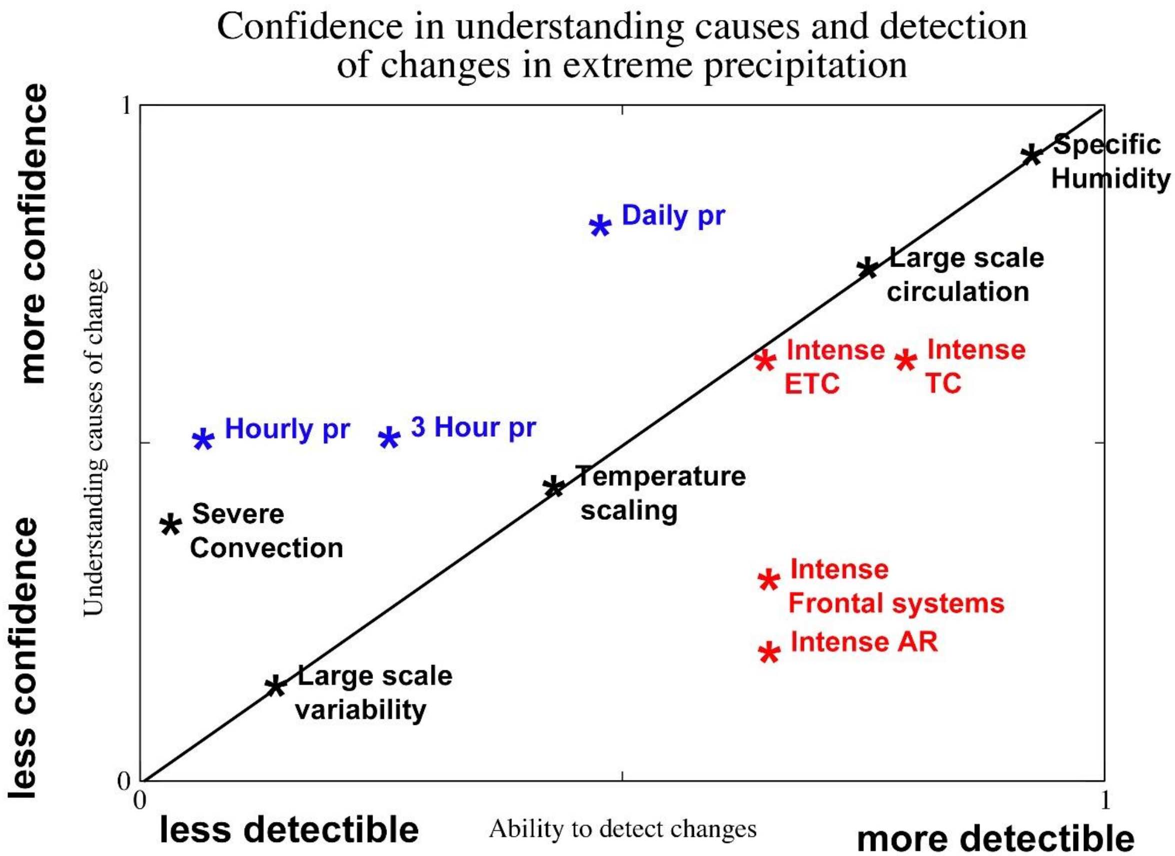


**Figure 3:** Confidence in understanding causes and detection of changes in extreme precipitation.

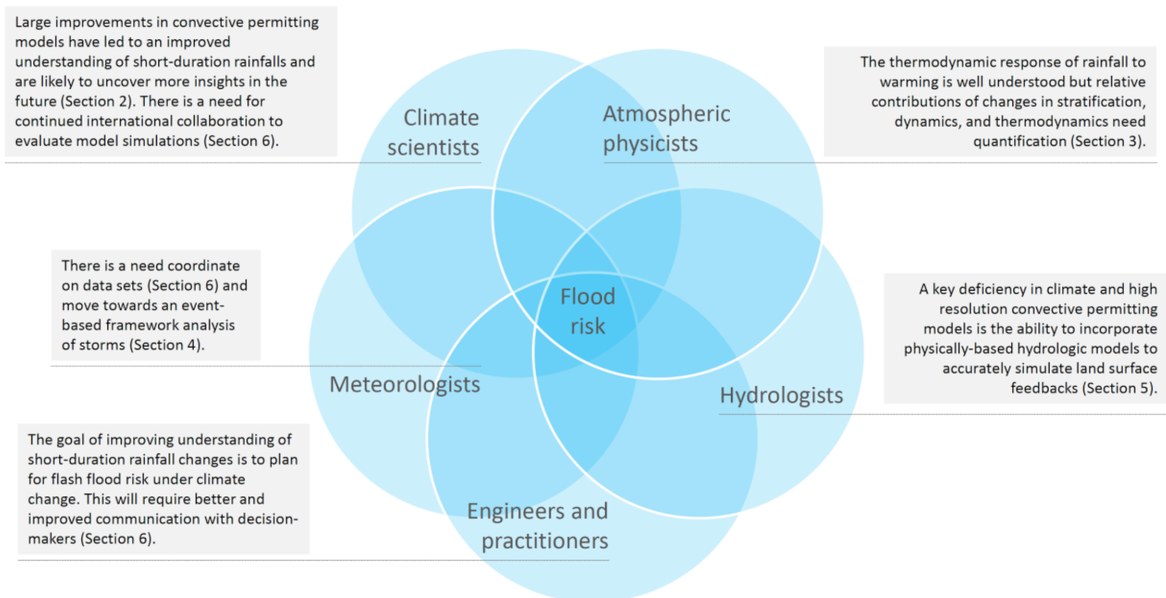


**Figure 4:** The INTENSE Project culminated in bringing together experts across multiple disciplines at the Royal Society, London to discuss recent advances in understanding climate change impacts on short-duration rainfall extremes and what is required to make further advances in the field. This diagram is conceptual only and aims to illustrate the crossovers between disciplines in a general sense. It is not to designed to be accurate in the placement of the Venn diagram circles.